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Hypervelocity Stars and the Galactic Center

Warren R. Brown

Smithsonian Astrophysical Observatory, 60 Garden St, Cambridge, MA 02138

wbrown@cfa.harvard.edu

1. INTRODUCTION

A massive black hole (MBH) will inevitably unbind stars from the Galaxy. Hills (1988) coined the term "hypervelocity star" (hereafter HVS) to describe a star ejected at $\sim$1000 km s^{-1} from a three-body interaction with a MBH. HVSs are a general consequence of MBHs in any galaxy (e.g. Sherwin et al. 2008), but the HVSs we can observe are the stars ejected from our own Galaxy.

Yu & Tremaine (2003) predict that Sgr A* ejects one HVS every $\sim 10^5$ yrs. Thus HVSs are rare: of the Galaxy's 10^{11} stars, there are only $\sim 10^3$ HVSs within 100 kpc of the Milky Way. Yet HVSs would be very interesting to find because HVSs provide unique constraints on the nature and environment of the central MBH.

In 2005 we reported the discovery of the first HVS: a 3 M$_\odot$ main sequence star traveling with a Galactic rest frame velocity of at least $+709 \pm 12$ km s^{-1}, more than twice the Milky Way's escape velocity at the star's distance of 110 kpc (Brown et al. 2005). This star cannot be explained by normal stellar interactions: the maximum ejection velocity from binary disruption mechanisms (Blaauw 1961; Poveda et al. 1967) is limited to $\sim$300 km s^{-1} for 3 M$_\odot$ stars (Leonard & Duncan 1988, 1990; Leonard 1991, 1993; Tauris & Takens 1998; Portegies Zwart 2000; Davies et al. 2002; Gualandris et al. 2005). Thus a massive and compact object is needed to accelerate a 3 M$_\odot$ star to an unbound velocity.

There is overwhelming evidence for a $\sim 4 \times 10^6$ M$_\odot$ MBH in the dense stellar environment of the Galactic center (e.g. Schödel et al. 2003; Ghez et al. 2005). The three-body exchange mechanism that may explain S-stars orbiting the MBH (Gould & Quillen 2003) is the same mechanism that may eject HVSs (Hills 1988). In this picture, S-stars are the former companions of HVSs (Ginsburg & Loeb 2006, 2007). Interestingly, the S-stars are main sequence B stars (Ghez et al. 2003; Eisenhauer et al. 2005; Martins et al. 2008), just like the observed HVSs described below.

In §2 we define HVSs in the context of unbound stars, and discuss how HVSs are made. In §3 we highlight recent HVS discoveries and discuss their nature. In §4 we explore the links between HVSs and the Galactic Center. We conclude in §5.

2. THEORETICAL CONSIDERATIONS

2.1. Defining an Hypervelocity Star

Following Hills (1988), we define HVSs by 1) their MBH origin and 2) their unbound velocities. An HVS ejected from the Milky Way travels on a nearly radial trajectory; the expected proper motion for a 50 kpc distant HVS is a few tenths of a milliarcsecond per year (Gnedin et al. 2005). Thus radial velocity directly measures most of an HVS's space motion. Deciding whether an HVS is unbound, however, requires knowledge of the star's location in the Galaxy.

Unfortunately, the Galactic potential is poorly constrained at distances > 50 kpc. Kenyon et al. (2008) discuss a form of the potential that, for the first time, fits the Milky Way mass distribution from 5 pc to 10^5 pc. Because the potential does not yield a formal escape velocity, they define unbound stars as having $v_{rf} > 200$ km s^{-1} at $R = 150$ kpc. This conservative definition yields a Galactic escape velocity of 360 km s^{-1} at 50 kpc and 260 km s^{-1} at 100 kpc. Xue et al. (2008), on the other hand, fit a halo potential model to the velocity dispersion of 2466 BHB stars located 5 kpc $< R <$ 60 kpc. The escape velocity resulting from the Xue et al. (2008) model is 290 km s^{-1} at 50 kpc and 190 km s^{-1} at 100 kpc.

2.2. Hyper-Runaways

Not all unbound stars are necessarily HVSs. Fast-moving pulsars, for example, are explained by supernova kicks (e.g. Arzoumanian et al. 2002). The star HD 271791 is the first example of an unbound "hyper-runaway" that was ejected from the outer disk, in the direction of Galactic rotation, when its former 55 $M_\odot$ binary companion exploded as a supernova (Heber et al. 2008; Przybilla et al. 2008a). Objects ejected in this manner are traditionally called runaways (Blaauw 1961). The term runaway also includes stars dynamically ejected from binary-binary encounters (Poveda et al. 1967).

Runaway star ejection mechanisms share a common velocity constraint: the physical properties of binary stars. Theoretically, the maximum ejection velocity from disrupting a binary is the binary orbital velocity, a velocity that increases with the mass of the stars. The theoretical maximum velocity is not realizable, however, because compact binaries that are too tight will merge due to energy loss from tidal dissipation and Roche-lobe overflow (e.g. Vanbeveren et al. 1998). While it is possible for an hyper-runaway to be confused with an HVS in the absence of proper motions, we estimate that $\sim$3 $M_\odot$ HVSs ejected from the Galactic Center are $\sim$100 times more common than hyper-runaways of the same mass (Brown et al. 2008). Hyper-runaways are limited by the rarity of massive stars and the requirement to avoid merging the compact binary progenitor.

2.3. How to Make Hypervelocity Stars

HVSs attain extreme velocities because the gravitational potential energy of a MBH greatly exceeds the binding energy of a stellar binary. In Hill's mechanism, the gravitational tidal force of a single MBH disrupts an approaching binary. One star is captured on an eccentric orbit around the MBH and, by conservation of energy, the other star escapes with a final velocity equal to the geometric mean of the $\sim 10^4$ km s^{-1} infall velocity (S0-16 had a pericenter velocity of 12000 km s^{-1}, Ghez et al. 2005) and the $\sim 10^2$ km s^{-1} binary orbital velocity. A star traveling 10^3 km s^{-1} at 1 pc will exit the Galaxy at 100 kpc at 400-500 km s^{-1} (Kenyon et al. 2008).

Yu & Tremaine (2003) further develop Hill's analysis to include the case of a binary MBH. While an equal-mass binary MBH is ruled out in the Galactic Center (Reid & Brunthaler 2004), theorists speculate that the massive star clusters in the Galactic Center may form intermediate mass black holes (IMBHs) in their cores. If such IMBHs exist, dynamical friction will cause them to in-spiral into the central MBH and eject HVSs along the way.

The properties of HVSs allow us to discriminate between the single MBH and binary MBH ejection mechanisms:

- *Velocity Distribution.* HVS ejection velocity depends weakly on the mass of the stellar binary $\propto (m_1 + m_2)^{1/3}$ for a single MBH (Hills 1988), but there is no such dependence on stellar mass for a binary MBH (e.g. Sesana et al. 2007b).
- *Ejection Rate.* A binary MBH has a larger cross-section and may eject $\sim 10\times$ more HVSs than a single MBH (Yu & Tremaine 2003).
- *Spatial Distribution.* A binary MBH preferentially ejects HVSs in its orbital plane, and thus produces a ring of HVSs around the sky (Gualandris et al. 2005; Levin 2006; Sesana et al. 2006; Merritt 2006).
- *Temporal Distribution.* As a binary MBH hardens and then merges, it will produce a distinctive burst of HVSs over $\sim 10^7$ yrs, during which HVS velocities will become systematically more energetic with time (Baumgardt et al. 2006; Sesana et al. 2006, 2007a).
- *Stellar Rotation Distribution.* HVSs ejected by a single MBH should be slow rotators, because stars in compact binaries have systematically lower $v \sin i$ due to tidal synchronization (Hansen 2007). On the other hand, single stars spun up and ejected by a binary MBH should be fast rotators (Löckmann & Baumgardt 2008).

HVSs may also be ejected by three-body interactions of single stars with stellar mass black holes clustered around the central MBH (O'Leary & Loeb 2008). This mechanism predicts that the lowest-mass HVSs will have the highest velocities, in contrast to Hill's mechanism.

2.4. Dark Matter

One interesting theoretical application for HVSs is as probes of the Galactic dark matter potential (Gnedin et al. 2005; Yu & Madau 2007; Wu et al. 2008). The dark matter paradigm makes specific predictions about the anisotropy of dark matter halos. Any deviation of an HVS's trajectory from the Galactic Center measures this anisotropy. Unlike tidal streams, HVSs integrate the Galactic potential out to very large distances. Interestingly, the Kenyon et al. (2008) potential suggests that HVSs may be much more sensitive to the bulge than to the halo. Moreover, the bulge potential acts as a high-pass filter: a star must be ejected at $\sim$800 km/s to reach 1 kpc.

3. OBSERVATIONS OF HYPERVELOCITY STARS

3.1. New HVSs

Observers have identified a remarkable number of unbound HVSs in the past 3 years. Following the discovery of the first HVS (Brown et al. 2005), Hirsch et al. (2005) reported a helium-rich subluminous O star leaving the Galaxy with a rest-frame velocity of at least +717 km s^{-1}. Edelmann et al. (2005) reported an 9 $M_{\odot}$ main sequence B star with a Galactic rest frame velocity of at least +548 km s^{-1}, possibly ejected from the Large Magellanic Cloud (LMC).

Brown et al. designed a targeted HVS survey that has discovered 13-17 new HVSs, plus evidence for a similar number of bound HVSs ejected by the same mechanism (Brown et al. 2006a,b, 2007a,b, 2008). Briefly, our survey uses Sloan photometry to select HVS candidates with the colors of late B-type stars (Figure 1). B-type stars have lifetimes consistent with travel times from the Galactic Center but are not a normally expected Galactic halo population. We highlight the latest results of our survey below.

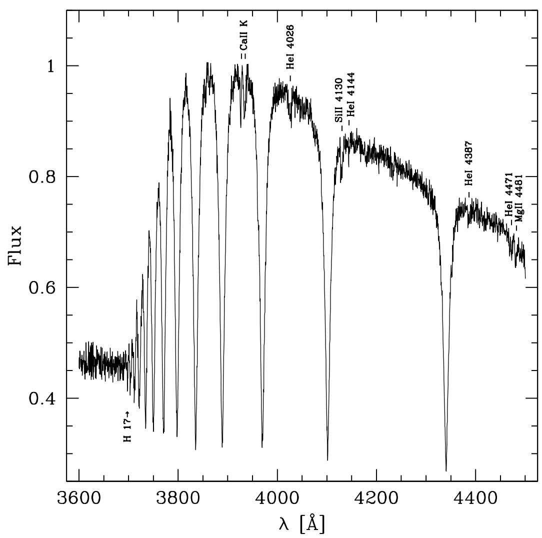
3.2. Velocity Distribution and Bound HVSs

Figure 2 plots the observed distribution of line-of-sight velocities, corrected to the Galactic rest-frame (see Brown et al. 2006b), for the B-type stars in our survey. The survey covers 7300 deg^2 of sky, with a surface density of $\sim$0.1 deg^{-2}. The 731 survey stars with $|v_{rf}| < 275$ km s^{-1} have a -1 ± 4 km s^{-1} mean and a 106 ± 5 km s^{-1} dispersion, consistent with a normal stellar halo population.

Remarkably, we observe 26 stars with $v_{rf} > 275$ km s^{-1} and only 2 stars with $v_{rf} < -275$ km s^{-1}. The escape velocity of the Milky Way at 50 kpc is $\sim$ 350 km s^{-1}, thus the 12 stars with $v_{rf} > 400$ km s^{-1} are clearly unbound (see also Figure 3). Ignoring the 12 unbound stars, there is less than a 10^{-5} probability of randomly drawing 14 stars with $275 < v_{rf} < 400$ km s^{-1} from the tail of a Gaussian distribution with the observed parameters. Thus the excess of positive velocity

outliers $275 < v_{rf} < 400$ km s^{-1} appears significant at the 4-σ level.

The positive velocity outliers demonstrate a population of possibly bound HVSs (Brown et al. 2007a,b). HVS ejection mechanisms naturally produce a broad spectrum of ejection velocities (e.g. Sesana et al. 2007b). Simulations of HVS ejections from the Hills mechanism suggest there should be comparable numbers of unbound and bound HVSs with $v_{rf} > +275$ km s^{-1} in our survey volume (Bromley et al. 2006). We find 14 unbound HVSs and 12 possibly bound HVSs with $v_{rf} > +275$ km s^{-1}, in good agreement with model predictions.



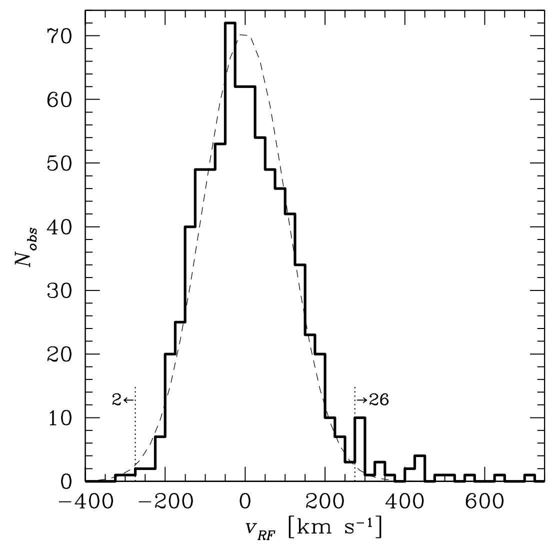


Fig. 1.— LEFT: Summed HVS spectrum, created from the weighted average of our observations of HVS1 and HVS4 - HVS10, shifted to rest frame. The spectral type is that of a B8 - B9 star. The wavelength difference between the pair of Ca II K lines, one from the HVSs and one from the local interstellar medium that appears in the spectra of HVS8 and HVS9, visibly indicates the large space motion of the HVSs, $\Delta\lambda/\lambda \sim 550$ km s^{-1}.

Fig. 2.— RIGHT: Observed radial velocity distribution, corrected to the Galactic rest-frame v_{rf}, for the 759 stars in our HVS survey. The best-fit Gaussian (*dashed line*) has dispersion 106 ± 5 km s^{-1}, excluding the 26 stars with $v_{rf} > +275$ km s^{-1}.

3.3. The Nature of HVSs

The significant absence of stars falling back onto the Galaxy around -300 km s^{-1} demonstrates that HVSs are short-lived (Brown et al. 2007b; Kollmeier & Gould 2007; Yu & Madau 2007). If bound HVSs had main sequence lifetimes greater than $\sim$1 Gyr, we would see them falling back onto the Galaxy, contrary to the observations. Given the color-selection of the HVS survey, the B-type HVSs must be 3-4 M$_\odot$ main sequence stars.

Follow-up observations have confirmed that four of the HVSs are main sequence stars: HVS1 is a slowly pulsating B variable (Fuentes et al. 2006), HVS3 is a 9 M$_\odot$ B star (Bonanos et al. 2008;

Przybilla et al. 2008b), HVS7 is a 3.7 $M_\odot$ Bp star (Przybilla et al. 2008c), and HVS8 is a rapidly rotating B star (López-Morales & Bonanos 2008).

The identification of HVSs as main sequence stars is in stark contrast to the halo stars in our survey, which are, presumably, evolved 0.6-1 $M_\odot$ stars on the blue horizontal branch (BHB). BHB stars among the HVSs would be exciting, however, because unbound BHB stars would allow us to probe the low-mass regime of HVSs.

Interestingly, HVS12 was previously classified as a BHB star in the BHB samples of Sirko et al. (2004) and Xue et al. (2008). The existence of 1 ± 1 BHB stars among our 14 unbound HVSs is consistent with predictions from Galactic center ejection models (Kenyon et al. 2008). A single HVS among the 1170 Sirko et al. (2004) BHB stars and the 10224 Xue et al. (2008) BHB candidates also shows the immense dilution due to stars in the Galactic halo. Our HVS survey works because we target stars that are bluer and/or fainter than the bulk of halo BHB stars.

3.4. A Possible HVS from the Large Magellanic Cloud

HVS3, the unbound star very near the LMC on the sky, has received considerable attention. HVS3 is a 9 $M_\odot$ B star of half-solar abundance, a good match to the abundance of the LMC (Bonanos et al. 2008; Przybilla et al. 2008b). Stellar abundance may not be conclusive evidence of origin, however. A- and B-type stars exhibit 0.5 - 1 dex scatter in elemental abundances within a single cluster, due to gravitational settling and radiative levitation in the atmospheres of the stars (Varenne & Monier 1999; Monier 2005; Fossati et al. 2007; Gebran et al. 2008; Gebran & Monier 2008). Yet because the 18 Myr lifetime of HVS3 is significantly shorter than its travel time from the Galactic Center, HVS3 may be the first evidence for a MBH in the LMC (Edelmann et al. 2005).

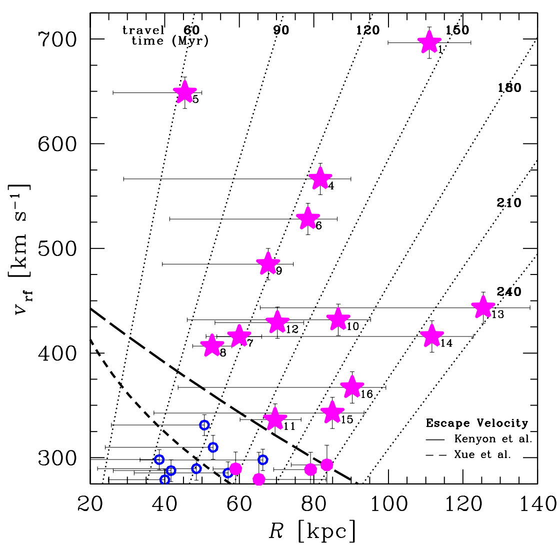
An LMC origin requires that HVS3 was ejected from the galaxy at ~ 1000 km s^{-1} (Przybilla et al. 2008b), a velocity that can possibly come from three-body interactions with an intermediate mass black hole in a massive star cluster (Gualandris & Portegies Zwart 2007; Gvaramadze et al. 2008). Perets (2008) shows that the ejection rate of 9 $M_\odot$ stars, however, is four orders of magnitude too small for this explanation to be plausible. The alternative explanation is that HVS3 is a blue straggler, ejected by the Milky Way's MBH. Theorists argue that a single MBH or a binary MBH can eject a compact binary star as an HVS (Lu et al. 2007; Perets 2008); the subsequent evolution of such a compact binary can result in mass-transfer and/or a merger that can possibly explain HVS3 (Perets 2008). Proper motion measurements, underway now with the *Hubble Space Telescope*, will determine HVS3's origin.

4. LINKS TO THE GALACTIC CENTER

4.1. Ejection History

If Sgr A* ejects a steady fountain of HVSs from the Galactic Center, then the space density of HVSs goes as $\rho \propto R^{-2}$ (Brown et al. 2006a; Kollmeier & Gould 2007; Kenyon et al. 2008). The volume sampled by a magnitude-limited survey is proportional to R^3. Thus, in the simplest picture, we expect the number of HVSs to have a linear dependence with R. Remarkably, the observed HVSs show just such a linear cumulative distribution (Brown et al. 2007b).

Figure 3 explores the history of stars interacting with Sgr A* in more detail. We calculate Galactic Center travel times (dotted lines) from the Kenyon et al. (2008) model, assuming the observed radial velocities are full space motions. HVS travel times span 60 - 240 Myr.



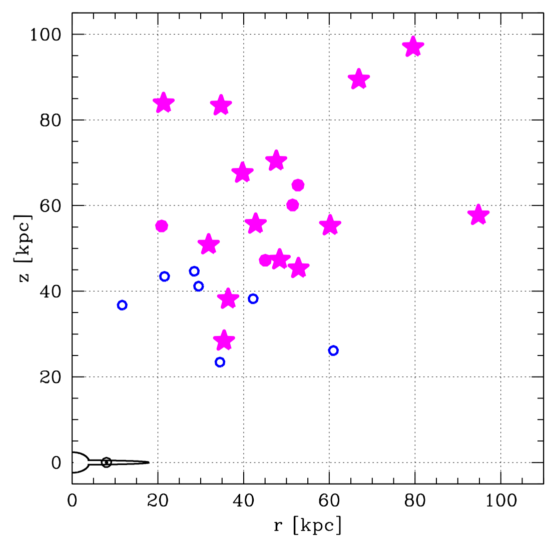


Fig. 3.— LEFT: Minimum rest-frame velocity vs. Galactocentric distance R for stars in our HVS survey (Brown et al. 2008). 14 unbound HVSs (*solid stars*) have velocities and distances exceeding the Kenyon et al. (2008) escape velocity model (*long dashed line*). 4 possible HVSs (*dots*) are in excess of the Xue et al. (2008) escape velocity model (*dashed line*). 8 possibly bound HVSs (*open circles*) are also indicated. Errorbars show the span of physically possible distance if the HVSs are BHB stars. Isochrones of travel time from the Galactic center (*dotted lines*) are calculated using the potential model of Kenyon et al. (2008), assuming the observed minimum rest frame velocity v_{rf} is the full space motion of the stars.

Fig. 4.— RIGHT: Location of our 14 HVSs (*stars*), the 4 possible HVSs (*dots*), and 8 possibly bound HVSs with $v_{rf} > 275$ km s^{-1} (*open circles*). z is the distance above the Galactic plane and r is the distance along the Galactic plane, such that $R = (r^2 + z^2)^{-0.5}$. For reference, we sketch the Milky Way and the Sun at $(r, z) = (8, 0)$ kpc.

Statistically, the set of HVSs favor a continuous ejection process. In other words, there is no evidence that a massive star cluster or IMBH has in-spiraled into the Galactic Center in the past couple hundred Myr, or at least one that produced a coherent burst of HVSs. Given the small number statistics, we cannot rule out that the 5 HVSs near ∼120 Myr, for example, come from a

single ejection event. However, the 5 HVSs near $\sim$120 Myr exhibit lower velocities at shorter travel times, in the opposite sense expected for ejections from an in-spiraling IMBH.

4.2. Stellar Population

Observed HVSs exit the Galaxy in $\sim$100 Myr and so they reflect the present stellar population near Sgr A*. In principle, we can constrain the parent mass function of HVSs by combining predictions of HVS rates with the observations. An HVS moving 500 km s^{-1} travels 100 kpc in 200 Myr, thus the Yu & Tremaine (2003) rate implies $\sim$2000 HVSs of all types to a depth of 100 kpc. Our magnitude-limited survey reaches the same depth over 1/6 of the sky, from which we infer 96 ± 20 unbound 3-4 M$_\odot$ HVSs within 100 kpc (Brown et al. 2007b). A Salpeter mass function (Salpeter 1955), integrated over the mass range 0.2-100 M$_\odot$ and normalized to 2000 stars, contains $\sim$20 stars between 3 and 4 M$_\odot$.

Perets et al. (2007) argues that massive perturbers, such as giant molecular clouds, scatter stars into Sgr A*'s "loss cone" much more efficiently than 2-body scattering. As a result, the Galactic Center may eject HVSs at a $\sim$10$\times$ greater rate than predicted by Yu & Tremaine (2003); in this case, the expected number of 3-4 M$_\odot$ HVSs in a Salpeter mass function increases to $\sim$200, in better agreement with observations.

The likelihood of finding low-mass HVSs depends sensitively on the mass function. If Sgr A* ejects stars with the present day mass function of the bulge, there is 1 unbound F-type HVS with $g' < 21.5$ per 50 deg^2 of sky (Kollmeier & Gould 2007). In the Galactic Center, there is some indication that the stellar mass function is top heavy (Maness et al. 2007). A Salpeter mass function predicts an order-of-magnitude lower density of F-type HVSs, 1 per $\sim$500 deg^2 (Brown et al. 2007b). The ratio of high- to low-mass HVSs thus provides a sensitive measure of the stellar mass function near Sgr A*.

4.3. Binary Fraction

HVSs are also linked to the properties of binaries. In the disk, nearly all O and B stars are in binaries, and a third of such binaries are equal-mass twins (Kobulnicky & Fryer 2007). It would be very interesting to know the multiplicity of stars in the Galactic Center, particularly the S-stars orbiting Sgr A*.

If HVSs are disrupted binaries, the former companions of HVSs are left on highly eccentric orbits around Sgr A* (Ginsburg & Loeb 2006). The orbital properties of the S-stars are thus linked to HVSs leaving the Galaxy today. Stars with main sequence lifetimes $\gtrsim$200 Myr were present when the known HVSs were ejected from the Galactic Center.

5. CONCLUSION

HVSs are fascinating because their properties are linked to Sgr A* and the stellar environment of the Galactic Center. A statistical sample of HVSs can address: 1) the nature of the MBH ejection mechanism, 2) the in-fall history of stars onto Sgr A*, 3) the types of stars orbiting Sgr A*, and 4) a unique measurement the shape of the Galaxy's dark matter potential. The challenge to observers is to find new HVSs and strengthen the connection between HVSs and the Galactic Center.

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